Improvements in Galileo-Mars Navigation Using the Viking Lander

F. B. Winn, M. P. Ananda, F. T. Nicholson, and E. W. Walsh
Navigation Systems Section

When the geocentric angular separation between two spacecraft is but a few degrees, navigational advantages may be achieved by navigating one spacecraft with respect to the other. In this dual-spacecraft navigation technique, radio metric data from the two spacecraft are not treated independently, but differenced to cancel common observable modeling errors.

In the circumstance of the Galileo Spacecraft flyby of Mars, the Mars Viking Lander I might provide a radio beacon that could be used to navigate Galileo past Mars. The Viking Lander has been operating on the Martian surface since July 20, 1976, and is expected to continue through 1990. It is intended that the navigational delivery accuracy capability of Galileo at Mars [25 km (lo)] is going to be met with interferometric angular measurements (VLBI) and range and range-rate measurements. Like VLBI, however, dual-spacecraft differenced range has little sensitivity to transmission media modeling errors, and to tracking-station location errors. Similarly, differenced range provides angular information about the separation between the Mars Viking Lander 1 and the Galileo Spacecraft. In covariance studies, dual-spacecraft differenced range coupled with conventional range and doppler is shown to estimate the Galileo-Mars flyby distance to better than 10 km (1 a), which is favorably comparable to the projected AVLBI performance. For the Galileo-Mars flyby, dual-spacecraft differenced range promises to be an excellent backup to VLBI if the Mars Viking Lander remains operational.

I. Introduction

The Galileo mission (Ref. 1) is a highly ambitious scientific project and this will be the first time an artificial satellite will be placed in an orbit around an outer planet. The major objectives of this mission are to maximize the number of flybys of the Galilean satellites and maximize the scientific return about the Jovian neighborhood. This and the constraints due to the shuttle-IUS (Interim Upper Stage) launch capability requires an interplanetary trajectory that includes a Mars flyby, which provides a needed gravity assist. Subsequent to this flyby, a propulsive maneuver is executed that places the spacecraft on a Jupiter-bound trajectory. To minimize the AV required for this maneuver, it is desired to pass as close to Mars as possible, consistent with planetary quarantine and spacecraft safety constraints. These constraints have placed the requirement on the navigation system that the delivery accuracy at Mars should be better than 20 to 25 km (1σ).

The conventional radio metric data, two-way doppler and range measurements from the Deep Space Network stations, can provide a heliocentric position accuracy for the Galileo spacecraft to an accuracy of about 3.5 km (lo). However, this does not include the uncertainty in the Mars ephemeris. When the projected Mars ephemeris uncertainty of 40 km (1 σ) is considered, the spacecraft position uncertainty at the Mars encounter point exceeds 50 km (1σ). Thus, the Galileo Project is planning to augment conventional radio metric two-way doppler and range with VLBI to achieve the required accuracy.

The VLBI method for navigational application has been extensively studied (Refs. 2 and 3); however, the concept is yet to be successfully demonstrated (Ref. 4). The potential application of the wideband VLBI system is discussed by Brown and Hildebrand (Ref. 5). This VLBI technique will be utilized in a differential mode with VLBI data referenced to an extragalactic radio source (EGRS) to difference out various common error sources. This imposes an additional requirement that the Mars ephemeris should be known with reference to an extragalactic radio source frame with an accuracy of better than 20 to 25 km (1 a). There exists an on-going activity, using Viking orbiter data, that is expected to provide the needed accuracy (Newhall, 1980, personal communication).

The Galileo project is also considering the utilization of the onboard optical system to achieve the desired accuracy. The use of optical data at Mars encounter has been successfully demonstrated during the Viking mission. It is not currently decided whether the optical system will be available for approach navigation at the Mars encounter phase.

Although the use of interplanetary beacons in general deep-space navigation has not been adequately investigated, the possible use of the Viking Lander as a beacon in Galileo navigation has been examined in covariance studies. Galileo-Viking, dual DSS range promises to improve conventional radio metric range and doppler orbit determination by a factor of 4. Its performance is favorably comparable to that of VLBI.

II. Radio Metric Measurements

Since the early 1960s, interplanetary navigation has been accomplished with such conventional radio metric measurements as the coherent two-way doppler data and two-way range data (Ref. 7). Measurement accuracies and model accuracies have been improved significantly over the years; however, the new anticipated navigation functions require alternate radio metric techniques to achieve the projected accuracy requirements.

A brief examination of the information content of these radio metric measurements is presented here. By processing one pass of coherent doppler data, the primary orbit parameters (the geocentric range rate, the right ascension, and declination of the spacecraft) can be determined. The accuracy with which these parameters can be determined is given by the following equations:

$$\sigma_{\dot{r}} = \sigma_{\dot{\rho}}$$

$$\sigma_{\alpha} = \frac{1}{\omega r_s \cos \delta} \pi \sigma_{\dot{\rho}}$$

$$\sigma_{\delta} = \frac{1}{\omega r_s \sin^- \delta} \frac{\pi}{2} \sigma_{\dot{\rho}}$$

where r, α, and δ are the geocentric range rate, the right ascension, and declination of the spacecraft respectively, $\dot{\rho}$ is the range rate measurement, ω is the spin rate of the earth, and r_s is the distance off the spin axis of the DSS.

Single-station range data taken over a pass provides the same information as that using doppler; however, the geocentric range information is better known. These, of course, are radial measurements. These measurements are corrupted primarily by transmission media modeling errors, station location errors, instrumentation errors, and unmodeled spacecraft accelerations. It is possible to minimize some of these errors by combining radio metric doppler and range from two stations and from two spacecraft into first and second differences. Errors that are common cancel. For first differenced range and doppler, spacecraft unmodeled accelerations, solar plasma corruptions, and spacecraft oscillator instability cancel, while ionospheric and tropospheric corruptions and station location and clock errors do not cancel. For dual-spacecraft-dual-station, differenced range and range-rate that is doubly differenced data, even the ionospheric, tropospheric, and station errors mostly cancel to yield relatively error-free observables. For doubly differenced range where one spacecraft is tied to the planet, even the planet ephemeris errors cancel to a large degree. The information that doubly differenced range does process is the relative right ascension and declination between two spacecraft.

$$\Delta^2 \rho = AZ \ [\cos \delta \, \Delta\delta]$$
$$- AL \ [\sin (\alpha - \theta) \cos \delta \, \Delta \alpha + \cos (\alpha - \theta) \sin \delta \, \Delta\delta]$$

with AZ and *AL* being the east-west and north-south projections of the baseline on the plane-of-sky, and $\Delta\alpha$ and A6 being the separation between the spacecraft and the beacon in right ascension and declination. θ is the local sidereal time.

III. Doubly Differenced Range Measurements

The use of differenced radio metric data from two spacecraft has been previously studied (Refs. 6 and 7). Dual-spacecraft-dual-station doubly differenced range simply carries the process one step further as suggested by Chao (Ref. 7).

Figure 1 shows the various components required to form this measurement. Stations A and B shown in Fig. 1 are separated by intercontinental distance. The two spacecrafts are shown as the Viking Lander (1) and the Galileo Spacecraft (2). Station A transmits a signal to the Lander and one round-trip light time later the range measurement is acquired. Range measurements from the Lander are acquired for about 10 to 15 minutes. Station B then transmits a signal to the Lander and ranging data are acquired a round-trip light time later. Then this procedure is repeated using both stations with Galileo. The doubly differenced range measurement can be formed from the following equation:

$$\Delta^2 \rho = \{\rho_{1A}(t_1) - \rho_{1B}(t_2)\} - \{\rho_{2A}(t_3) - \rho_{2B}(t_4)\}$$

where ρ_{ij} ($i = 1, 2$; $j = A, B$) are the two-way range measurements, and t_K ($k = 1, 2, 3, 4$) are the corresponding station acquisition times.

As discussed earlier, each two-way range component of this measurement is susceptible to various error sources with most of the errors thought common to multiple links. Thus, the differencing process is expected to achieve cancellation of most of these errors. A theoretical error' budget has been formed to account for those errors that do not completely cancel in the formation of dual spacecraft differenced range (Table 1). The assumptions made in generating this error budget are that the Viking Lander/Galileo separation angle is about 5 degrees, the data are taken near Mars opposition and at about 0.7-AU distance, and two stations observe the Lander for approximately 15 minutes each and then observe the Galileo spacecraft for the same: amount of time. Also, the measurements are assumed to be taken at about 25-deg elevation angle. This may not be totally realistic because in general the observations from at least one of the two stations has a low elevation (10 to 15 deg) when the spacecraft is visible from two widely separated stations. However, 90 percent of the error budget stems from the system noise term and not the media errors. A root-sum-square (rss) error of about 2.2 m is obtained for a doubly differenced range measurement, and this is assumed to be random because the error is mostly due to the thermal white noise.

Since the achievable navigation accuracy using the technique described in this article strongly depends on the assumed measurement error, it is important to validate the measurement accuracy using existing spacecraft. Thus, near-simultaneous ranging experiments have been already conducted using the Viking Orbiter 1 and Lander 1, and are being planned using the Voyager 1 and 2 spacecraft.

Before the Orbiter became inoperative in July 1980, there were two opportunities to acquire doubly differenced range: 5 June 1980 (this attempt failed), and 28 June 1980. The 28 June experiment was successful. The difference between the Lander and Orbiter relative range residuals was 3.4 m. Details of this data validation process are contained in the Appendix. To date, this is the only empirical assessment of doubly differenced range rms error. Voyager may provide additional opportunities in the near future.

IV. Galileo-Mars Flyby Navigation

The Galileo mission presents a number of navigational challenges (Ref. 1); one of the more stringent of these relates to the Mars flyby phase of the mission.

Galileo Project plans call for the Galileo Spacecraft to flyby Mars -200 km ($\sigma_d = 25$ km) above the planet's surface (Ref. 1). To achieve this accurate flyby, two new technological advances must be accomplished: one, the Mars ephemeris must be improved to better than 25 km (lo); and two, a wide-band Very Long Base Interferometry (VLBI) technology must be developed that will permit the Galileo Spacecraft and Mars trajectories to be defined relative to a quasar inertial reference frame. Both efforts are underway and offer a means to reduce the Galileo-Mars relative trajectory errors, and also to obtain. observables free from the preponderance of the Deep Space Station (DSS) location effects and transmission media effects.

What is shown here is that doubly differenced range from Viking Lander 1 and the Galileo Spacecraft can, like VLBI, achieve the Project Mars flyby requirement, providing the Lander survives. However, doubly differenced range is (1) essentially independent of planetary ephemeris uncertainty, and (2) is operationally simpler to use than VLBI.

There are 43 opportunities to obtain Viking range during the Galileo Mars approach. Viking has been programmed to transpond range on those 43 occasions (Table 2). This limit in opportunities exists because

(1) Galileo cruise time from Earth to Mars is -93 days (March 1984 to June 1984).

(2) Lander thermal and power constraints permit only two 13-minute contiguous ranging segments per day.

(3) The Lander is not always in view during overlapping portions of tracking station view periods of Mars.

These joint Viking-Galileo ranging opportunities are shown on Fig. 2 and listed in Table 2. Since the Martian day ($\sim 24^h 37^m 23^s$) and Earth day are of comparable length, for a given hour angle of the Earth the relative geometry between DSS baselines and the Lander changes very slowly. Each baseline, in turn, can view the Lander for nearly eight days continuously.

The DSS identification numbers 14, 43, and 63 represent the Deep Space Network Stations at Goldstone, California; Canberra, Australia; and Madrid, Spain, respectively.

Each baseline's performance is not only time dependent, but is also governed by the alignment of the baseline with respect to the Galileo-Mars direction at encounter (Fig. 3). In essence, first differenced range from a spacecraft provides information as to the direction of that spacecraft with respect to the baseline but only in the direction of the baseline. Orthogonal to the baseline, there is no information. When measurements from two spacecraft are differenced to obtain $\Delta^2\rho, \Delta^2\rho$ defines the component of the earth-centered angular separation between the two spacecraft in the baseline direction. Figure 3 shows the baseline orientations relative to the Mars-Galileo direction at encounter. The DSS 43 - DSS 63 baseline, which is approximately 4-deg offset, yields the strongest information concerning the flyby distance, while the DSS 63 - DSS 14 (~12-deg offset) and the DSS 14 - DSS 43 (~60-deg offset) baselines provide progressively less information.

V. Covariance Analysis

The covariance analysis performed in this paper assumed a maximum likelihood estimator with gaussian errors on the observations. The assumed observations include two-way coherent doppler data from the Galileo Spacecraft using the three Deep Space Network stations continuously, one Doppler measurement every hour, one range measurement from the Goldstone station every day and the available doubly differenced range measurements as shown in Fig. 2. Since the dynamical state parameters are nonlinear functions of the measurements, the observation equations are linearized and the results obtained are based on a linear estimator. When a standard maximum likelihood estimator is constructed, the computed statistics based on data noise errors do not reflect the effect of model errors in the solution. Thus, the statistics must be adjusted to account for their effects.

The measurement equation can be written in this form:

$$z = Ax + Cp + e$$

where z is the vector of measurements, x the vector of estimated parameters, p the vector of model parameters whose effects on the estimated parameters are to be investigated, and e the vector of measurement errors. A weighted least squares estimator of $(\hat{\mathbf{x}})$ can be obtained by

$$(\hat{\mathbf{x}}) = [\mathbf{A}^T\mathbf{P}^{-1}\mathbf{A}]^{-1}\mathbf{A}^T\mathbf{P}^{-1}\mathbf{z}$$

with the assumption that p is a random vector of zero mean with covariance P_p, $E(e) = o$, cov (e) = P and $\mathbf{E}(\mathbf{p}\,\mathbf{e}^T) = 0$ and the covariance of $(\hat{\mathbf{x}})$ is given by

$$\mathbf{P}_x^c = \mathrm{Cov}\ (\hat{\mathbf{x}}) = \mathbf{P}_x + \mathbf{P}_x\mathbf{A}^T\mathbf{P}^{-1}\ \mathrm{CP}_p\ \mathbf{C}^T\mathbf{P}^{-1}\mathbf{A}\mathbf{P}_x$$

where $P_x = (\mathbf{A}^T\mathbf{P}^{-1}\mathrm{A})^{-1}$ is the noise covariance matrix. The matrix $\mathbf{P}_x^c$ is known as the "consider" covariance matrix and the matrices A and C are the partial derivatives of the measurement with respect to the estimated and the consider parameters. Both station locations and Mars ephemeris parameters are treated as "considered" parameters. Only the Galileo trajectory is being estimated. The a priori uncertainties of the parameters are given in Table 3.

In this covariance analysis the doppler data accuracy is assumed to be 1 mm/s with a 60-s averaging time, the range data is weighted with l-km accuracy. The doubly differenced range measurements are assumed to be accurate to 2 m. Figure 4 presents the results of the covariance analysis. The flyby distance uncertainty is below the 10-km level about 25 days before the encounter.

If $\Delta^2\rho$ is not employed, conventional range and doppler estimates of the Galileo-Mars flyby distance are dominated by the Mars ephemeris uncertainty of 40 km (1 σ). If conventional and VLBI data are employed with an improved Mars ephemeris, 25 km (1 σ), the uncertainty in the estimates is still dominated by the ephemeris uncertainty and is always greater than 25 km (1σ).

Estimates of the flyby distance based on doubly differenced range have uncertainties often smaller than the ephemeris sigmas or tracking station location standard deviations because of the like influence of these error sources on the individual range measurements that are differenced to develop a doubly differenced range measurement. The ephemeris and station uncertainties cancel. Figure 5 illustrates how the influences of ephemeris and tracking station location uncertainties are less when $\Delta^2\rho$ is included in the covariance. Here only the Galileo state is estimated. The Mars ephemeris and station location are considered in the manner previously discussed. The uncertainty of the estimate of the Mars encounter distance of Galileo due to the Mars ephemeris uncertainty ($\sigma_d|_{\text{Mars Ephemeris}}$) and due to station uncertainty ($\sigma_d|_{\text{DSS Locations}}$) rapidly decreases as the tracking data arc of conventional data and $\Delta^2\rho$ become longer. When conventional data only is reduced, sensitivities to these consider parameters do not diminish.

VI. Summary and Conclusion

A newly proposed navigation technique utilizing two-way range data taken nearly simultaneously from two spacecraft has been analyzed and the results clearly show that the relative position of one spacecraft to the other can be determined with an accuracy depending only on the accuracy of the measurement. It is also shown that this technique can be applied during the Mars flyby phase of the Galileo mission. Covariance analyses show that the improvement in flyby navigation accuracy is significant compared to the conventional ground-based radio metric navigation. Since the achievable navigation accuracy strongly depends on the assumed measurement accuracy, experiments were conducted to evaluate the measurement accuracy: A single experiment using Viking Lander and Orbiter was viable for this purpose and the data reductions indicate that the expected accuracy can be attained. Since the Viking Orbiter is no longer operational, future experiments will be conducted using Voyager 1 and 2 spacecraft to increase the confidence level of the measurement accuracy.

This analysis has shown that the use of beacons for interplanetary navigation, specifically for target related navigation, will be of significant value. Thus, the utilization of interplanetary beacons should be a part of the next generation navigation technology development program.

References

1. Rourke, "Navigation of the 1982 Jupiter Orbiterprobe Mission," presented at AAS/AIAA Astrodynamics Specialist Conference, Jackson Hole, Wyoming, Sept. 7-9, 1977.
2. Melbourne, W., and D. Curkendall "Radio Metric Direction Finding: A New Approach to Deep Space Navigation," presented at AAS/AIAA Astrodynamics Specialist Conference, Jackson Hole, Wyoming, Sept. 7-9. 1980.
3. Curkendall, D., "Radio Metric Technology for Deep Space Navigation, A Development Overview," presented at AIAA/AAS Astrodynamics Conference, Palo Alto, California, Aug. 7-9, 1978.
4. Christensen, C. S., et al., "Results of a Demonstration of the Use of AVLBI Data for Precise Navigation of Interplanetary Spacecraft," presented at AIAA/AAS Astrodynamics Conference, Danvers, Mass., Aug. 11-13, 1980.
5. Brown, D., and C. Hildebrand, "Wideband AVLBI for Deep Space Navigation," presented at IEEE PLANS 80 Conference, Atlantic City, New Jersey, Dec. 1980.
6. Melbourne, W., "Navigation Between the Planets," *Scientific American*, Vol. 234, No. 6, June 1976.
7. Chao, C. C., et al., "Improvements in Navigation Resulting from the Use of Dual Spacecraft Radio Metric Data," presented at the AIAA/AAS Astrodynamics Conference, 76-834, San Diego, California, Aug. 18-20, 1976.
8. Mayo, A. P., et al., "Lander Locations, Mars Physical Ephemeris, and Solar System Parameters: Determination from Viking Lander Tracking Data," *J. Geophys. Res.* Vol. 82, No. 27, 1977.
9. Hildebrand, C., et al., "Viking Satellite Orbit Determination," presented at AIAA 15th Aerospace Sciences meeting, Los Angeles, California, Jan. 24-26, 1977.
10. Komarek, T., and T. Otoshi, "Terminology of Ranging Measurements and DSS Calibrations," *DSN Progress Report* 42-36, Jet Propulsion Laboratory, Pasadena, Calif., Dec. 1976.
11. Chao, C., *New Tropospheric Range Corrections with Seasonal Adjustment*, TR 32-1526, Vol. VI. Jet Propulsion Laboratory, Pasadena, Calif., 1971.

Appendix A

Viking Lander/Orbiter Data Processing

The experiment that was conducted on June 28, 1980 employed the Deep Space Stations at Goldstone, California (DSS 14) and Madrid, Spain (DSS 63). The time sequence of data acquisitions is given in Fig. 6. The Orbiter was first tracked by DSS 63. Two-way coherent doppler and range measurements were obtained. Subsequent to this, DSS 14 was used to acquire the Lander, and range and doppler measurements were generated. After 13 minutes of data acquisition, DSS 14 handed over to DSS 63 tracking of the Lander. Both range and doppler measurements were obtained for about 13 minutes. Subsequent to this, DSS 14 was used to track the Orbiter. This completed the cycle with four independent tracking links.

From tracking the Lander for an extensive period of time, the Lander location with respect to the dynamic center of Mars has been determined very accurately (Ref. 8). The current uncertainty of the Lander location is about 300 m. The Orbiter position can be determined by processing doppler tracking data. With sufficient data, the Orbiter position can be determined with an accuracy better than 10 km, Thus, the Lander relative position of the Orbiter is known to better than 10 km, and doubly differenced range measurement residuals can be generated and the measurement accuracy can be evaluated.

The Orbiter position (state vector) is determined by processing the coherent two-way doppler data. This is accomplished by estimating state parameters (position and velocity components of the Orbiter) only. However, the low-order gravity coefficients are included in the trajectory model equations, The best fit to the orbit of the Orbiter is obtained when continuous tracking data over the whole orbit, except for a couple of hours near the periapsis, are available. When the periapsis data are available, these are often deleted out to desensitize the effects of unmodeled higher degree coefficients of the gravity field. In this experiment, although there were sufficient tracking data, the doppler data were not continuous throughout the orbit, The tracking data (doppler) were available from the Australian station (DSS 43) about one hour after periapsis, for about 2.75 hours. Then there was a gap of about 1.75 hours without any data. After this, the Spain station (DSS 63) provided the data for about 6.5 hours. Then there were no tracking data for about 7.5 hours. Once again DSS 43 provided about three hours of doppler data. Even though the tracking data were not available continuously over the orbit, previous studies (Ref. 9) have shown that the accuracy degradation is relatively small if the available data are distributed over the orbit.

The postfit residuals from the Orbiter data are shown in the Fig. 7. On both sides of the periapsis, the data are taken with a frequency of one measurement every minute. The rest of the data are with a frequency of one measurement every 10 minutes. The data with both sample sizes are weighted accordingly with a data weight of 15 mHz with l-minute averaging time, in the data reduction process. The standard deviation of the postfit data residuals is less than 10 mHz indicating that the residuals do not contain any orbit related systematic signature.

As discussed previously, the doubly differenced range data are generated by explicitly differencing two differenced range data points from two different sources. In this case, one of the sources is the Viking Orbiter. Thus, it is necessary to examine the residuals of the differenced range points of the Orbiter. This is accomplished simply by generating range residuals of the data from both stations, The range residuals are obtained by passing the raw range measurements through the best fit orbit. The range residuals have to be adjusted for (1) ground station calibration, (2) transponder delay, and (3) the media effects.

A discussion of ground station calibration is given by Komarek and Otoshi (Ref. 10). The calibration for media effects is achieved by adjusting for the troposphere effects using a troposphere table based on pressure and temperature models for the stations as a function of elevation angle (Ref. 11). Ionospheric effects are calibrated either by using Faraday rotation data or multifrequency data from the spacecraft. Faraday rotation data have been used here, There is a modeling error in the Faraday rotation calibration for the ionospheric effects primarily due to the mapping of the Faraday rotation data to the line of sight of the spacecraft. However, this error is significantly less than the estimated accuracy of this new data type.

The range residuals are shown in the Fig. 8. The residuals are expressed in meters, A range bias of 13.5 m is observed between DSSs 63 and 14.

The Lander data is processed in a manner similar to the Orbiter range data, however, the Lander location is known a priori, and the parameters related to the Lander location are given in Table 3. The Lander range residuals are generated by differencing the computed values of range points based on assumed models from the observed range points. The range residuals, after appropriate calibration is applied, are shown in Fig. 9. It is clear from this figure that there exists a bias of about 10.1 m between DSSs 63 and 14 in the same direction as observed in the case of the Orbiter data. When the doubly differenced range observable is formed, these two biases are also differenced and the resulting bias is about 3.4 m and this represents the measurement accuracy of this data type.

Both Orbiter and Lander range residuals (Figs. 8 and 9) show that the scatter within a single station measurement is considerably small (< 1 m) as predicted by theoretical error budget. This scatter is mostly due to the system noise, depending on the spanned-bandwidth of the ranging code. The range bias between two stations is often introduced by the range calibration error. Errors in both ground station calibration and media calibration can cause the 3.4-m bias. Theoretically, this bias is expected to cancel when two spacecraft data are differenced. However, the cancellation due to media errors is a function of the spatial separation of the two spacecraft and the time separation in the data acquisition. In this experiment, the spatial separation is negligible (< 0.1 deg). However, the data acquisition time separation between the Orbiter and the Lander is over an hour. Thus, a part of the residual bias may stem from temporal changes in media. Cancellation of errors due to ground station calibration is achievable if the same instrumentation configuration is utilized in acquiring both Orbiter and Lander ranging data. In this experiment, although most of the instrumentation used in tracking the Orbiter and the Lander is the same, different receivers were employed. Thus, it is possible that the remaining residual bias in the doubly differenced data is due to the error in the calibration values and this is consistent with the currently expected calibration accuracy. More doubly differenced range data is required to understand its noise characteristics.

Table 1. Doubly differenced range data error budget

Source	Error (la), cm
Instrumentation:	
Station clock stability (15 min)	4
Station delay calibration	0
SNR (Thermal noise; (S-band with 2-MHz spanned band width)	200
Waveform distortion	88
Spacecraft delay	28
Media	
Troposphere (25-deg elevation)	20
Ionosphere (25-deg elevation)	6
Solar wind	15
	rss: -222 cm

Table 2. Viking Lander direct link ranging opporhnities for Galileo navigation, 1994

Point	DSS Baseline[a]	Date
1	63-14	22 March 84
2	63-14	23 March 84
3	63-14	24 March 84
4	63-14	25 March 84
5	63-14	26 March 84
6	14-43	29 March 84
7	14-43	30 March 84
8	14-43	31 March 84
9	1443	1 April 84
10	14-43	2 April 84
11	14-43	3 April 84
12	14-43	5 April 84
13	14-43	6 April 84
14	43-63	14 April 84
15	43-63	15 April 84
16	43-63	16 April 84
17	43-63	17 April 84
18	43-63	18 April 84
19	63-14	25 April 84
20	63-14	26 April 84
21	63-14	27 April 84
22	63-14	29 April 84
23	63-14	30 April 84
24	63-14	1 May 84
25	14-43	4 May 84
26	14-43	6 May 84
27	14-43	7 May 84
28	14-43	8 May 84
29	14-43	9 May 84
30	14-43	10 May 84
31	14-43	11 May 84
32	43-63	17 May 84
33	43-63	18 May 84
34	43-63	20 May 84
35	43-63	21 May 84
36	43-63	22 May 84
37	14-43	23 May 84
38	63-14	27 May 84
39	63-14	29 May 84
40	63-14	30 May 84
41	63-14	31 May 84
42	63-14	1 June 84
43	63-14	2 June 84

[a]DSS 14 (Goldstone, California)
DSS 43 (Woomera, Australia)
DSS 63 (Madrid, Spain)

Table 3. Error analysis parameters

Parameter	A priori σ
Galileo state	$\sigma_x = \sigma_y = \sigma_z = 10^7$ km $\sigma_{\dot{x}} = \sigma_{\dot{y}} = \sigma_{\dot{z}} = 100$ km/s
Mars ephemeris	$\sigma_{radial} = 10$ km, $\sigma_{intrack} = 40$ km $\sigma_{out\ of\ plane} = 70$km
Station locations	$\sigma_{long} = 3$ m, $\sigma_{r_s} = 1.5$ m $\sigma_{r_z} = 15$ m
Viking Lander locations	$\sigma_x = 10.0$ m $\sigma_x = 40.0$ m $\sigma_z = 300.0$ m
Mars mass	$\sigma = 0.1$ km^3/s^2

r_s = distance off the spin axis

r_z = distance off the earth equator plane

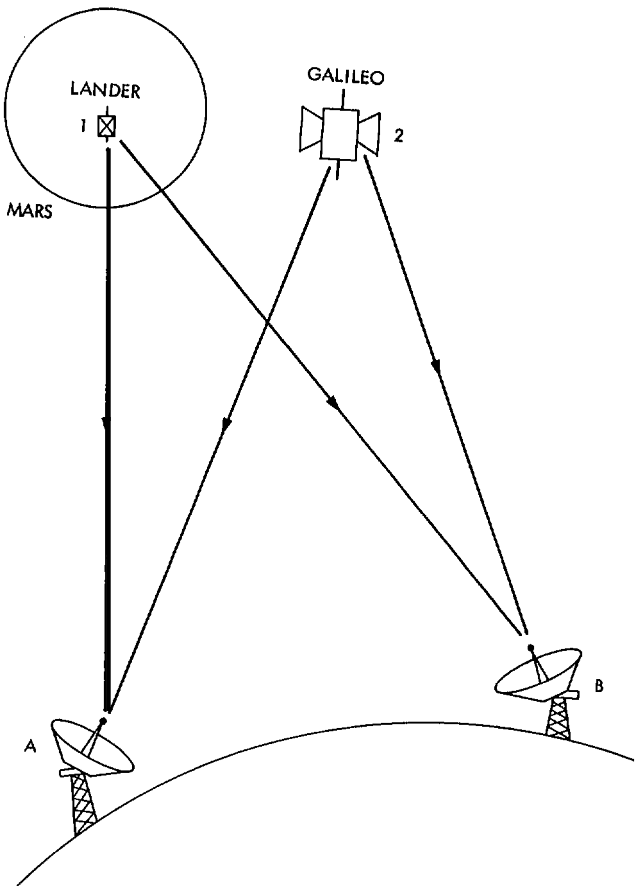

Fig. 1. Doubly differenced range data links

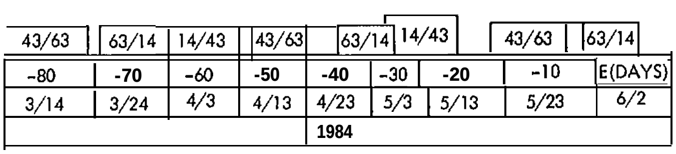

Fig. 2. Lander/Galileo viewing opportunities

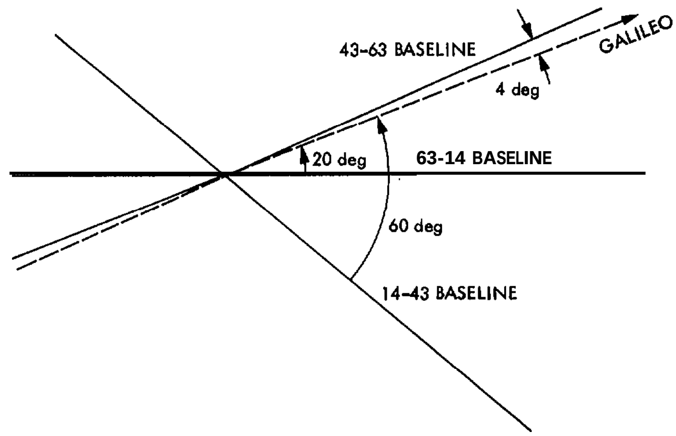

Fig. 3. Deep Space Station baselines projected in the plane normal to the Galileo approach asymptote at the Mars encounter

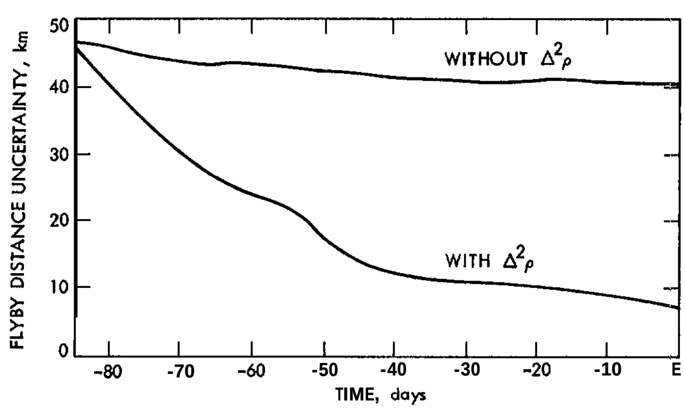

Fig. 4. Covariance analysis results

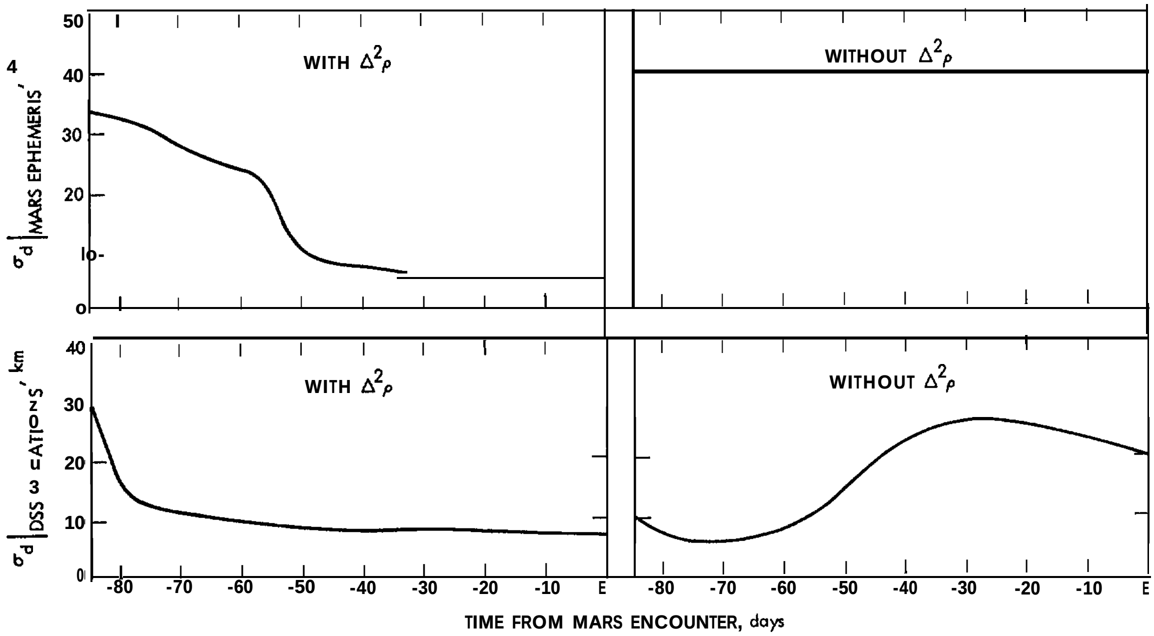

Fig. 5. Reduced sensitivity consider parameters

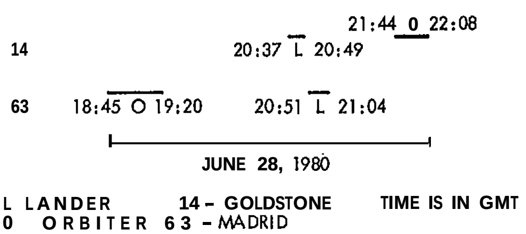

Fig. 6. Lander/Orbiter tracking sequence

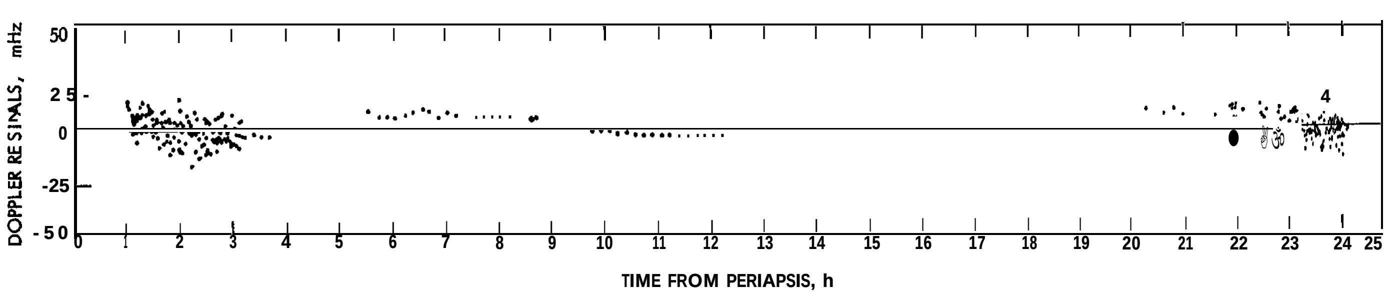

Fig. 7. Orbiter doppler data postfit residuals

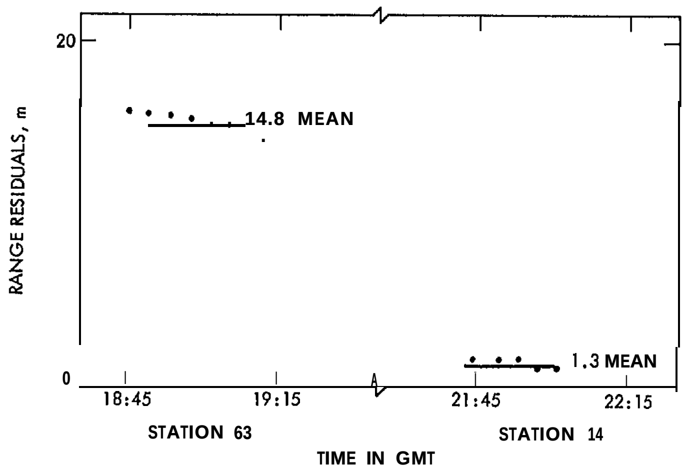

Fig. 6. Orbiter range residuals

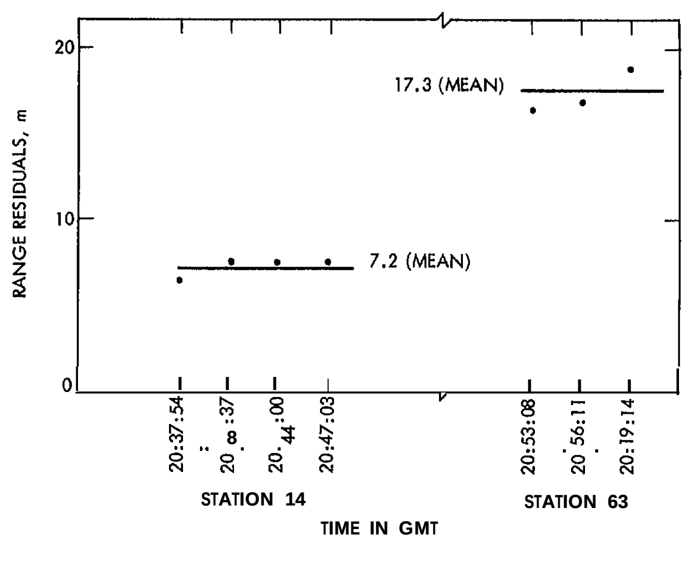

Fig. 9. Lander range residuals